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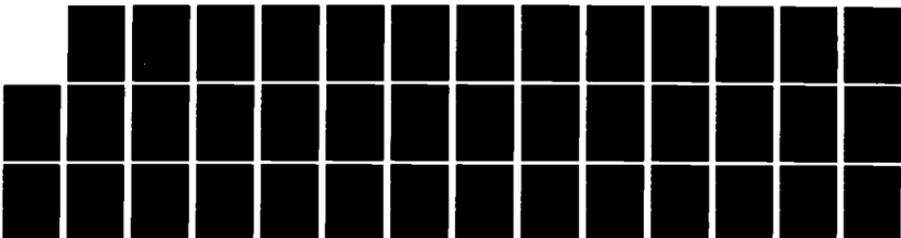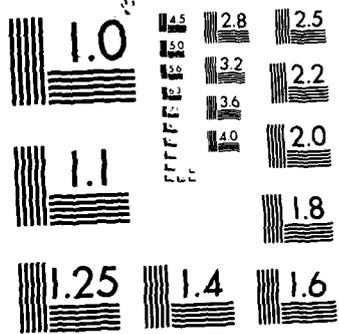
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TRANSITION FROM CONDUCTIVE TO CONVECTIVE HEAT TRANSFER IN FLUID-FILLED POROUS MATERIALS

BY A. A. CAMPOLATTARO,
    G. R. LAIB

RESEARCH AND TECHNOLOGY DEPARTMENT

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The heat transfer mechanism for an infinite, horizontal, fluid-saturated, homogeneous, porous slab is analyzed by assuming the validity of Darcy's law. By perturbing the equilibrium configuration, it is shown that there exists a stability condition for the temperature gradient β such that for

$$\beta > \frac{4\pi^2}{K} \frac{\kappa}{\partial h^2}$$

(where κ is the thermal diffusivity, K is the permeability, h is the thickness through which the thermal gradient is established and λ is the bulk thermal expansion coefficient of the fluid), the mechanism of heat transfer changes from conductive to primarily convective. The role of this stability criterion in DDT (deflagration-to-detonation transition) or porous explosives and propellants is discussed.

FOREWORD

The conditions for transition from primarily conductive to convective heat transfer in a simple porous material have been analyzed, assuming the validity of Darcy's law. A stability criterion, which may apply in the Deflagration-to-Detonation Transition (DDT) of porous explosives and propellants, has been derived and discussed. This work should be of interest to those concerned with propellant safety and DDT in porous reactive materials.

Approved by:

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Energetic Materials Division

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I. INTRODUCTION

In 1948 Lapwood[1] analyzed the heat flow in an infinite, horizontal, fluid-saturated, homogeneous, porous slab. By adopting the mathematical technique used by Lord Rayleigh in 1916[2] in an analogous problem (the stability of a liquid layer heated from below), Lapwood showed that the flow is not always stable, but that there exists the same stability condition that Rayleigh had found in the case of the liquid layer. The stability condition states that, if the temperature gradient exceeds a certain critical value, one has the onset of instabilities associated with fluid convection.

This analysis was conducted assuming zero viscosity, which drastically simplifies the problem. Only recently, Kassoy and Zebib[3,4,5] have investigated the same problem by taking into account the viscosity and using the more realistic configuration of a confine' medium.

The onset of instabilities corresponds to a transition from a conductive to convective heat transfer which manifests itself in a dramatic change in the thermal conductivity characteristics of the porous material. As early as 1933, Kannuluik[6] showed that the thermal conductivity of powders shows a sharp increase when they are permeated by a gas. For example, for evacuated powders such as carborundum, the thermal conductivity is typically of the order of 0.1×10^{-5} cal/cm-sec-$^{\circ}$C. However, when carborundum powder is filled with hydrogen, whose conductivity is 38.0×10^{-5}, in the same units, the conductivity of the powder increases to 300×10^{-5} cal/cm-sec-$^{\circ}$C, 3×10^{3} times the thermal conductivity of the evacuated powder!

[1]Lapwood, E. R., "Convection of a Fluid in a Porous Medium," Proc. Camb. Phil. Soc., 44, 508-521, 1948.

[2]Lord Rayleigh, "On Convection Currents in a Horizontal Layer of Fluid, When the Higher Temperature is on the Under Side," Phil. Mag., 6, 32, 529-546, 1916.

[3]Kassoy, D.R. and Zebib, A., "Variable Viscosity Effects on the Onset of Convection in Porous Media," Phys. of Fluids, 12, 18, 1649-1651, 1975.

[4]Zebib, A. and Kassoy, D. R., "Onset of Natural Convection in a Box of Water-Saturated Porous Media with Large Temperature Variation," Phys. of Fluids, 20 (1), 4-9, 1977

[5]Zebib, A., "Onset of Natural Convection in a Cylinder of Water-Saturated Porous Media," Phys. Fluids, 21 (4), 699-700, 1978.

[6]Kannuluik, W. G., "Conduction of Heat in Powders," Proc. Roy. Soc., A141, 144-158, 1933.

This phenomenon can be explained only by assuming that a convective process is established and that the heat is transferred to the grains of powder by collision with the fluid molecules.

The effect of the gas imbedded in a porous medium is illustrated in Figure 1, which also shows the importance of grain sizes and density for carborundum powder (See Table I for density and particle size parameters for carborundum). The effect of different gases imbedded in the powder (hydrogen and air) is also shown. Figure 1 shows also that the conductivities increase with pressure, although they tend to reach a plateau at pressures of the order of one atmosphere, so that for high pressures one can assume that the conductivities become pressure-independent. This seems reasonable if one considers the data shown on curves of conductivity vs pressure in Figure 2 for two typical gases--namely, air and hydrogen.

These results appear to play an important role in the deflagration-to-detonation transition in high explosives because, as is well known, this transition is preceded by another transition, that from conductive to convective burning. An analysis to determine the conditions necessary for this transition will now be considered.

II. STABILITY ANALYSIS

The xy-plane contains a horizontal slab of a fluid-saturated homogenous, porous material with thickness h, so that $0 \leq z \leq h$.

In absence of viscosity, the Navier-Stokes equation reduces to the Euler equation:

$$\rho \, \frac{D\vec{V}}{Dt} = -\vec{\nabla}p - \vec{F} \tag{1}$$

with

$$\frac{D}{Dt} = \frac{\partial}{\partial t} + \vec{V} \cdot \vec{\nabla} \tag{2}$$

ρ, the density, $\vec{V}$, the macroscopic velocity of the element of fluid at the point (x,y,z), whose components are u,v, and w, with p, the pressure, and $\vec{F}$, the system of forces acting on the element of fluid. This force $\vec{F}$ consists of two components, the weight $\vec{W} = (0,0,\rho g)$, with g, the acceleration of gravity, and a resistance component for the porous material given by Darcy's law, so that one has for the total force:

$$\vec{F} = \frac{\rho g}{K} \, \vec{V} + \rho g \vec{k} \tag{3}$$

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K being the permeability and $\vec{K}$, the unit vector in the direction of the z-axis. The gravitational component $\rho g \vec{k}$, although negligible in comparison to the Darcy term (which, in the case of low permeability materials, such as propellants, is large) has been included for the sake of completeness.

To the fluidynamic equation, one must add the heat conduction equation:

$$\frac{D\theta}{Dt} = \kappa \nabla^2 \theta \tag{4}$$

where θ is the temperature and κ the thermal diffusivity. To Equations 1-4, one must also add two other equations, a continuity equation:

$$\frac{1}{\rho} \frac{D\rho}{Dt} = -\vec{\nabla} \cdot \vec{V} \tag{5}$$

and an equation for thermal expansion:

$$\rho = \rho_c (1 - \alpha \theta) \tag{6}$$

where ρ_c is the value of ρ at $\theta = 0$, and α is the bulk thermal expansion coefficient.

Equations (1)-(6) can be linearized by assuming that velocity and the departures of temperature, density, and pressure from the equilibrium state are small so that second order terms can be assumed negligible.

If the variations in density as well as the $(\vec{V} \cdot \vec{\nabla})\vec{V}$ term are considered negligible, one has

$$\rho \frac{\partial \vec{V}}{\partial t} = -\vec{\nabla}P - \frac{\rho g}{K} \vec{V} - \rho g \vec{K}, \tag{7}$$

$$\frac{D\theta}{Dt} = \kappa \nabla^2 \theta, \tag{8}$$

$$\vec{\nabla} \cdot \vec{V} = 0, \tag{9}$$

$$\rho = \rho_c (1 - \alpha \theta) \tag{10}$$

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The subscript "0" labels the parameters in the equilibrium state. The system is assumed perturbed from the equilibrium state and the perturbations are, as usual, considered small. We have:

$$\theta = \theta_0 + \theta \approx - \beta z + \theta \ , \tag{11}$$

$$P = p_0 + p \approx - \rho_0 g z + p \ , \tag{12}$$

$$\rho_0 = \rho_c \ (1-\alpha\theta_0) \ , \tag{13}$$

$$\rho = \rho_c \ 1-\alpha(\theta+\theta_0) \ = \rho_0 - \rho_c\alpha\theta \ , \tag{14}$$

where β is the temperature gradient.

Since the term $\vec{V} \cdot \vec{\nabla\theta}$ is negligible, equation (8) reads

$$- \beta w + \frac{\partial\theta}{\partial t} = \kappa\nabla^2\theta. \tag{15}$$

By taking the divergence of (7), since (10) holds, one has

$$\nabla^2 P - \rho_c g\alpha \frac{\partial\theta}{\partial z} = 0. \tag{16}$$

The third component of (7) gives

$$\rho_0 \frac{\partial w}{\partial t} = - \frac{\partial p}{\partial t} - \frac{\rho_0 g}{K} w - \rho_0 g + g\rho_c\alpha\theta \ , \tag{17}$$

and with (15) and its time derivative, w can be eliminated, and one has

$$- \frac{\partial p}{\partial z} + \rho_c g\alpha\theta = \frac{1}{\beta} \ \rho_c\left(\frac{\partial}{\partial t} + \frac{g}{K}\right)\left(\frac{\partial}{\partial t} - \kappa\nabla^2\right)\theta + \rho_0 g \tag{18}$$

By taking the Laplacian of (18) and the z derivative of (16), the pressure also can be eliminated, and one readily has the fourth order partial differential equation for the temperature θ,

$$\left(\frac{\partial}{\partial t} + \frac{g}{K}\right)\left(\frac{\partial}{\partial t} - \kappa\nabla\right)^2 \nabla^2\theta = g\alpha\beta\,\nabla_1^2\theta \ , \tag{19}$$

where ∇_1^2, is the partial Laplacian, namely

$$\nabla_1^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} \ . \tag{20}$$

Let us now consider a simple case, with the following boundary conditions:

$$\theta = 0 \quad \text{at } z = 0 \quad \text{and } z = h \tag{21}$$

$$\frac{\partial^2\theta}{\partial z^2} = 0 \quad \text{at } z = 0 \quad \text{and } z = h \tag{22}$$

The search for a solution of Equation (19) of the form

$$\theta = R(x,y,t)\, Z(z) \tag{23}$$

imposes on z, through the boundary conditions (21) and (22), the following conditions,

$$Z(0) = Z(h) = 0 \ , \tag{24}$$

$$Z''(0) = Z''(h) = 0 \ , \tag{25}$$

so that by taking

$$Z(z) = A \sin \omega z \tag{26}$$

one has

$$\sin \omega h = 0 \quad \text{i.e., } \omega h = n\pi. \tag{27}$$

Now we try a solution of the form

$$\theta = A\sin\lambda x \sin\mu y \sin\frac{n\pi}{h} z \, e^{\nu t}. \tag{28}$$

By substitution into Equation (19), one has

$$\left(\nu + \frac{g}{K}\right)\left\{\nu + \frac{\kappa}{h^2}(a^2 + n^2\pi^2)\right\}\left(a^2 + n^2\pi^2\right) = g\alpha\beta a^2 \tag{29}$$

where

$$a^2 = h^2(\mu^2 + \lambda^2), \tag{$\;$}$$

$$\alpha_1 = \frac{g}{K}, \tag{$\;$}$$

$$\alpha_2 = \frac{\kappa}{h^2}(a^2 + n^2\pi^2), \tag{32}$$

$$\alpha_3 = \frac{g\alpha a^2}{a^2 + n^2\pi^2}\beta, \tag{33}$$

and Equation 29 reads

$$(\nu + \alpha_1)(\nu + \alpha_2) = \alpha_3, \tag{34}$$

which admits the following roots

$$\nu = -\,1/2\,(\alpha_1 + \alpha_2) \pm 1/2\,\sqrt{(\alpha_1 - \alpha_2)^2 + 4\alpha_3} \tag{35}$$

When ν is complex, its real part, $-1/2(\alpha_1 + \alpha_2)$, is always negative and the perturbation decays with time, since α_1 and α_2 are positive. If we require the perturbation to persist then the roots must be real and positive, i.e.,

$$(\alpha_1 - \alpha_2)^2 + 4\alpha_3 > 0 \ , \tag{36}$$

and

$$-(\alpha_1 + \alpha_2) \pm \sqrt{(\alpha_1 - \alpha_2)^2 + 4\alpha_3} > 0 \ . \tag{37}$$

If $\beta > 0$, (35) is certainly satisfied, and the roots are real.

The value of $\beta = \beta_{cr}$ which results in a value of zero for ν is the one for which, when $\beta < \beta_{cr}$, the perturbation dies down, and when $\beta > \beta_{cr}$, it increases exponentially. This value is found by solving the equation:

$$(\alpha_1 - \alpha_2)^2 + 4\alpha_3 = (\alpha_1 + \alpha_2)^2 \ , \tag{38}$$

$$\alpha_3 = \frac{(\alpha_1 + \alpha_2)^2 - (\alpha_1 - \alpha_2)^2}{4} \ , \tag{39}$$

$$\alpha_3 = \alpha_1 \alpha_2 \ , \tag{40}$$

which gives

$$\beta_{cr} = \frac{\kappa}{K\alpha h^2} \frac{(a^2 + n^2 \pi^2)^2}{a^2} \tag{41}$$

The minimal value of $\beta_{cr} = \overline{\beta}_{cr}$ is obtained, since n is an integer, for $n = 1$ and for a value of a, such that the function $\dfrac{a^2 + \pi^2}{a}$ is minimum. This minimum is readily recognized for $a^2 = \pi^2$, so that

$$\overline{\beta}_{cr} = \frac{4\pi^2 \kappa}{K\alpha h^2} \ , \tag{42}$$

and for

$$\beta < \frac{4\pi^2 \kappa}{K\alpha h^2} \ , \qquad\qquad (43)$$

the flow is stable and the perturbation rapidly dies exponentially. For

$$\beta > \frac{4\pi^2 \kappa}{K\alpha h^2} \ , \qquad\qquad (44)$$

the perturbation increases exponentially and the flow is unstable. This represents the condition for the transition from conductive to convective heat transfer in a fluid-filled porous material in the hypothesis that Darcy's law holds.

III. THE ROLE OF THE STABILITY CONDITION IN THE BURNING OF POROUS MATERIALS AND PROPELLANTS

The stability condition discussed in the previous pages appears to be of particular interest in the study of the combustion of porous material and propellants. It involves all the typical parameters one expects to encounter in the process; namely, the temperature gradient, the thermal diffusivity, the thermal expansion coefficient of the fluid filling the pores, the permeability of the porous material, and the thickness of the material through which the thermal gradient is established.

The stability condition states that when the temperature gradient β is such that

$$\beta > \frac{4\pi^2 \kappa}{K\alpha h^2} \ ,$$

the heat transfer dramatically changes character from conductive to primarily convective. Analogous criteria are expected to apply to the burning of modern solid propellants with a high content of solid materials. In this case, during combustion, ahead of the flame, there exists a layer of propellant-heated, although not yet burning. Although the temperature is initially insufficient to ignite the propellant, it increases with time and can reach a value at which the solvent and the binder begin to evaporate or decompose so that a porous layer whose thickness varies with time, begins to form ahead of the flame. The previous considerations then apply. In the case of small propellant grains, the total burning time is probably too short for such a phenomenon to occur. The advent of longer range solid-propellant requires longer burning propellant grain, so that the process described above could develop.

IV. AN ESTIMATE OF THE THERMAL GRADIENT ESTABLISHED IN A PROPELLANT GRAIN

The problem of heat transfer in thermal conductors when the heat sources are moving, is a problem of foremost importance in several fields, such as metal welding, and many studies have been made on the subject.[7,8] However, since, from a mathematical point of view, the rigorous treatment is of great difficulty, this analysis has been confined to the quasi-stationary regime. This regime is experimentally verified[9] and is seen in the fact that, if the sample is long enough, the temperature ahead of the moving source rapidly approaches a constant value. In different terms, an observer who is moving with the source does not detect, after a certain time, any change in the temperature distribution in the sample ahead of the source. While the quasi-stationary solution is often of practical utility, the transient regime is important in many cases.

For the sake of simplicity, we will make an assumption, which will be removed in a successive study, that the sample is non-reactive. The burning process is then schematized by substituting for the flame front a heat source which moves along the x-axis with a constant speed v and a constant heat rate q. The evaluation of the temperature distribution $T(x,y,z,t)$ will be determined by the heat conduction equation:

$$\frac{\partial^2 t}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial t^2} = 2\lambda \frac{\partial T}{\partial t} , \tag{45}$$

where

$$2\lambda = \frac{c\rho}{k} , \tag{46}$$

c being the specific heat of the solid material, ρ its density and k the thermal conductivity coefficient of the material. The transformation

$$\xi = x - vt, \tag{47}$$

brings Equation (45) into the following form:

[7]Campolattaro, A. A., Numerical Modelling of the Burning of Highly Exothermic Mixtures, NSWC report 1977 (To be published).

[8]Rosenthal, D., The Theory of Moving Sources of Heat and Its Applications to Metal Treatment, Trans. Amer, Soc. Mech Engrs.,68 849-866, 1946, and included bibliography.

[9]Bornefeld, H., Temperature Measurement in Fusion Welding, Technische Zentralblatt Fur Praktische Metal Bearbeitung Vol. 43, pp. 14-18, 1933.

$$\nabla^2 T + 2\lambda v \frac{\partial T}{\partial \xi} - 2\lambda \frac{\partial T}{\partial t} = 0. \tag{48}$$

where the Laplacian is the Eulerian one, i.e. the operator Laplacian involving the coordinates system moving with the heat source, i.e.

$$\nabla^2 = \frac{\partial^2}{\partial \xi^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}. \tag{49}$$

By putting

$$T = T_o + e^{-\alpha \xi} \, \phi(\xi, y, z, t) \tag{50}$$

where T_o is the initial temperature, Equation (48) becomes

$$\nabla^2 \phi + 2(\lambda v - \alpha) \frac{\partial \phi}{\partial \xi} - 2\lambda \frac{\partial \phi}{\partial t} + \alpha(\alpha - 2\lambda v) \, \phi = 0. \tag{51}$$

and by taking

$$\alpha = \lambda v, \tag{52}$$

the term $\frac{\partial \phi}{\partial \xi}$ can be eliminated and one has

$$\nabla^2 \phi - 2\lambda \frac{\partial \phi}{\partial t} - (\lambda v)^2 \, \phi = 0. \tag{53}$$

By putting

$$\phi = e^{-\frac{\lambda v^2 t}{2}} \, \psi, \tag{54}$$

Equation (53) reduces further to the ordinary heat conduction equation, i.e.

$$\nabla^2 \psi - 2\lambda \frac{\partial \psi}{\partial t} = 0 \ , \tag{55}$$

The solution of (48) which satisfies the boundary condition that at the flame ($\xi = 0$), the temperature remains constant and equal to T_f, for the one-dimensional case, will be

$$T - T_o = e^{-\lambda v \xi} \ e^{\frac{-\lambda v^2}{2} t} \ \psi(\xi,t) \ , \tag{56}$$

so that the initial condition for ψ is

$$\psi(\xi,t) = 0 \qquad \text{for } t = 0, \tag{57}$$

and at the boundary,

$$T_f - T_o = e^{\frac{-\lambda v^2}{2} t} \ \psi(0,t) \ , \tag{58}$$

Equation (55) must be integrated with the initial and boundary conditions given by

$$\psi(\xi,t) = 0 \qquad \text{for } t = 0, \tag{59}$$

$$\psi(\xi,t) = (T_f - T_o) \ e^{\frac{\lambda v^2}{2} t} \qquad \text{for } \xi = 0. \tag{60}$$

This integral is readily found[10]

---

[10]Carslaw, H. S., and Jaeger, J. C., Conduction of Heat in Solids, Oxford at the Clarendon Press, II Ed., 1959, page 63.

$$e^{\lambda v \xi} \; e^{\frac{\lambda v^2 t}{2}} \; (T - T_o) =$$

$$\sqrt{\frac{\lambda}{2\pi}} \; (T_f - T_o)\xi \int_o^t \frac{e^{\frac{\lambda v^2 t'}{2}} \; e^{-\frac{\lambda \xi \mu^2}{2(t-t')}}}{(t - t')^{3/2}} \; dt \qquad (61)$$

By putting

$$t - t' = \mu, \qquad (62)$$

Equation (61) reads

$$T - T_o = \sqrt{\frac{\lambda}{2\pi}} \; (T_f - T_o)\xi \; e^{-v\xi} \int_o^t \mu^{-3/2} \; e^{\frac{-\lambda v \mu^2}{2}} \; e^{\frac{\lambda \xi^2}{2\mu}} \; d\mu , \qquad (63)$$

or

$$T - T_o = \sqrt{\frac{\lambda}{2\pi}} \; (T_f - T_o)\xi \; e^{-\lambda v\xi} \int_o^t \mu^{-3/2} \; e^{-\frac{\lambda}{2} \frac{\xi^2 + v^2 \mu^2}{\mu}} \; d\mu \qquad (64)$$

which gives the temperature at any time t and at a distance ξ from the propagating flame.

An easy check of this solution can be made by setting v=0 in Equation (64) to determine whether or not it reduces to the solution for a semi-infinite slab with the boundary at ξ=0 kept at constant temperature T_f and the initial temperature constant and equal to T_o, which is a classical problem.[11]

For v=0, Equation (64) reads:

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[11]Carslaw, H. S., and Jaeger, J. C., Conduction of Heat in Solids.

$$T - T_o = \sqrt{\frac{\lambda}{2\pi}} \, (T_f - T_o)\xi \int_o^t \mu^{-3/2} \, e^{-\frac{\lambda}{2}\frac{\xi^2}{\mu}} \, d\mu \, , \tag{65}$$

which, by setting

$$x = \sqrt{\frac{\lambda}{2\mu}} \, \xi \, , \tag{66}$$

readily gives:

$$T - T_o = (T_f - T_o) \, \text{erfc} \, \xi \sqrt{\frac{\lambda}{2t}} \, , \tag{67}$$

which is indeed the solution given by Carslaw and Jaeger.[12]

It is also useful to evaluate the steady-state solution of Equation (48). Neglecting the time derivative in Equation (48), we have as the steady-state equation,

$$\nabla^2 T + 2\lambda v \, \frac{\partial T}{\partial \xi} = 0. \tag{68}$$

By putting

$$T = T_o + e^{-\lambda v\xi} \, \phi. \tag{69}$$

Equation (65) becomes

$$\nabla^2 \phi - (\lambda v)^2 \, \phi = 0, \tag{70}$$

which reduces to, in the one-dimensional case:

$$\frac{d^2\phi}{d\xi^2} - (\lambda v)^2 \, \phi = 0, \tag{71}$$

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[12] Carslaw, H. S. and Jaeger, J. C., Conduction of Heat in Solids, p. 60.

whose general integral is

$$\phi = Ae^{\lambda v \xi} + Be^{-\lambda v \xi} , \qquad (72)$$

with A and B as arbitrary constants of integration.

The boundary conditions for T which are of physical interest are:

$$T = T_f \text{ for } \xi = 0, \text{ and } \lim_{\xi \to \infty} T = T_o, \qquad (73)$$

and, from (69) and (72), one readily has

$$T = T_o + (T_f - T_o) e^{-2v\lambda \xi} . \qquad (74)$$

If T_r is the temperature at which some chemical reaction or phase change occurrs within one or more of the components of a mixture undergoing combustion, then the distance ξ_r, ahead of the flame, at which the burning material has reached temperature T_r is readily evaluated from (74), and one has

$$\xi_r = \frac{1}{\lambda v} \ln \frac{T_f - T_o}{T_r - T_o} \qquad (75)$$

This distance is only of interest if we have

$$\xi_r > v\tau \qquad (76)$$

where τ is the reaction time at the temperature T_r. Equation (76) combined with Equation (75) gives the following relation among the physical parameters of the system for a reaction or phase change to occur:

$$\lambda v^2 \tau < \ln \frac{T_f - T_o}{T_r - T_o} \qquad (77)$$

Equation (64) may be integrated numerically to evaluate the temperature at any time τ at a distance ξ from the propagating flame for materials whose burn velocity (v), flame temperature (T_f) and thermal diffusivity are known. These parameters are summarized for three materials in Table 2. Equation (64) was integrated for each material at various distances (ξ) ahead of the flame as a function of time. The results are shown in Figures 3(a), 3(b) and 3(c). The time required to establish a "steady-state" temperature varies directly with the distance ahead of the flame (ξ) and the thermal diffusivity, as expected.

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Calculations were also made to determine "steady-state" temperature rise as a function of distance ahead of the flame front by integrating at each of 10 distances numerically until convergence is reached. The results of these calculations for materials listed in Table I are shown in Figures 4(a), 4(b), and 4(c). The calculated temperature as $\xi \to 0$, though not shown in these figures, does indeed approach the flame temperature. From these calculations, an estimate can be made of the thermal gradient existing in porous materials burning conductively to assess when the transition conditions for the onset of convective flow are reached. Measurements of the permeability (K) of these propellants as well as the thermal expansion coefficient of their combustion products (α) must be made in order to check the validity of the model.

V. CONCLUSIONS

A condition has been found which governs the transition from conductive to convective burning in nonreactive analogs of porous propellants and explosives. The relevant physical parameters in the transition are, as one would expect, the temperature gradient in the material, its thermal diffusivity, and the thermal expansion coefficient of its combustion gases. It has been previously well-established[13,14] that the conductive-convective flow transition precedes that from deflagration-to-detonation. A mechanism has been proposed whereby an initially non-porous propellant grain may become porous through conductive heating ahead of the flame and subsequent phase change or thermal degradation of propellant ingredients. The establishment of a sufficiently high thermal gradient throughout this newly-formed porous layer, whose thickness increases with time, then defines the condition for the onset of primarily-convective flow.

Experimental work will be done in the near future to obtain the physical parameters necessary to verify the validity of the condition for conductive-convective flow transition in porous materials and its role as a precursor to DDT.

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[13]Griffith, N., and Gloocock, J. M., "The Burning to Detonation of Solid Explosives," J. Chem. Soc., 4154, 1960.

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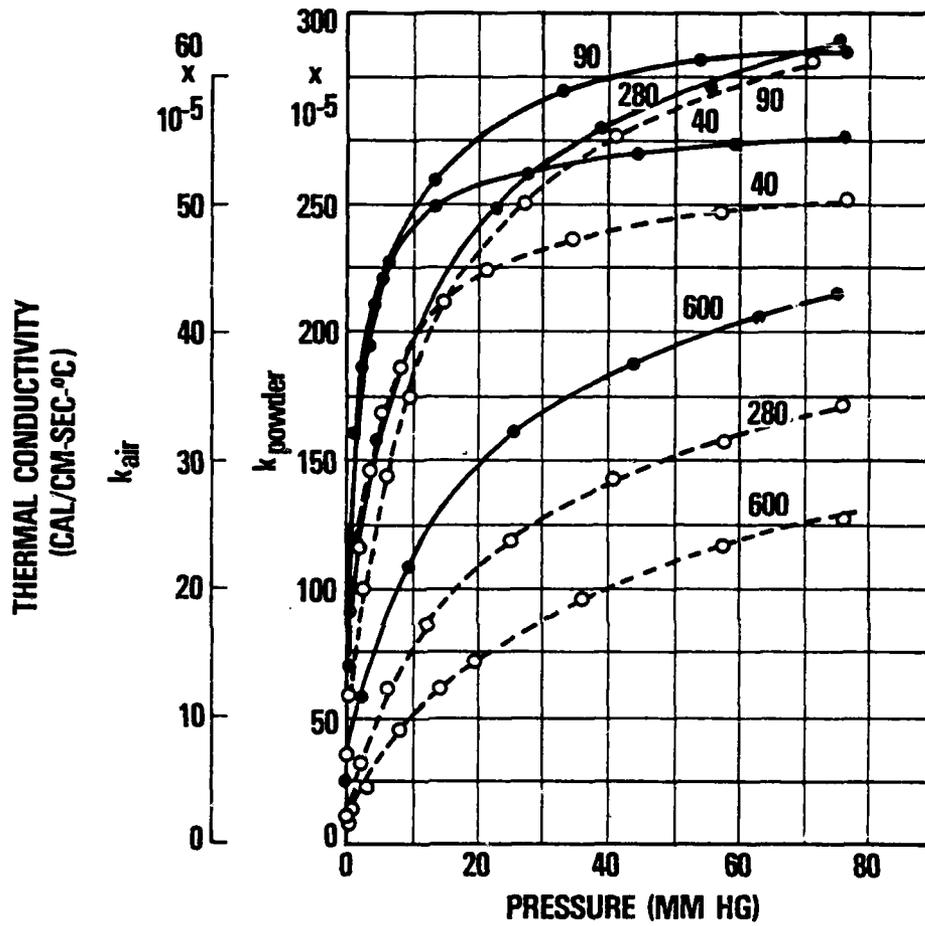
FIGURE 1. THERMAL CONDUCTIVITY (k) CURVES FOR CARBORUNDUM
WITH H_2, SHOWN IN DOTTED LINE, AND FILLED WITH AIR,
SHOWN IN SOLID LINE, VS PRESSURE (REF. 6)
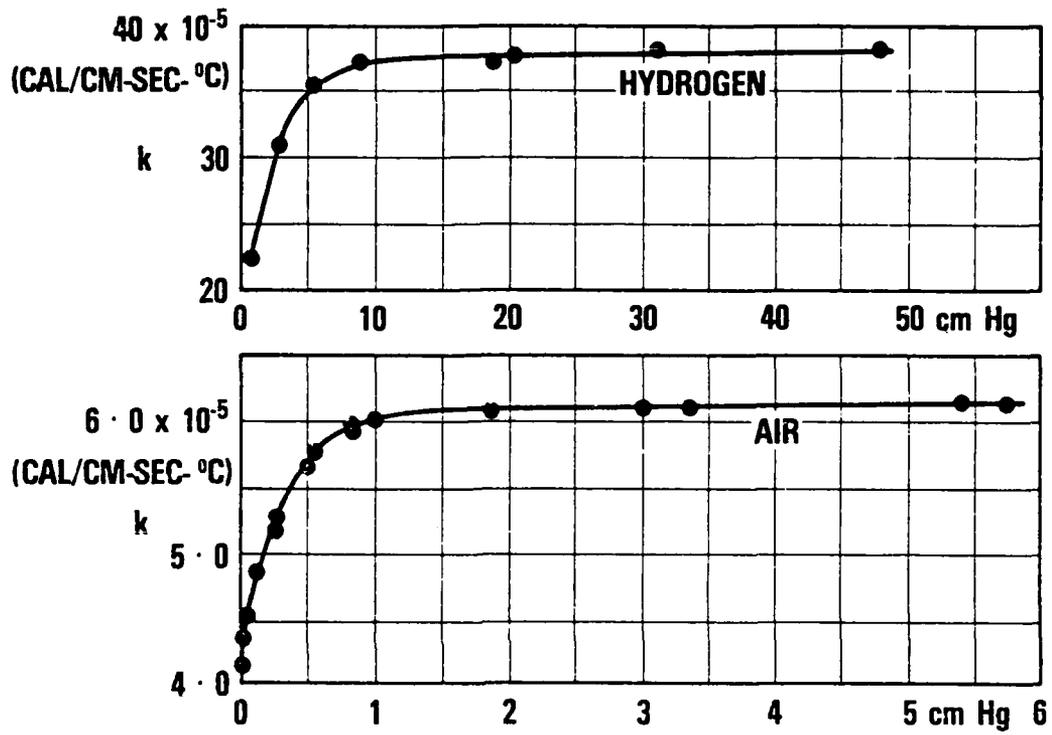
FIGURE 2. CONDUCTIVITY OF HYDROGEN AND AIR AS A FUNCTION
OF PRESSURE (REF. 6)
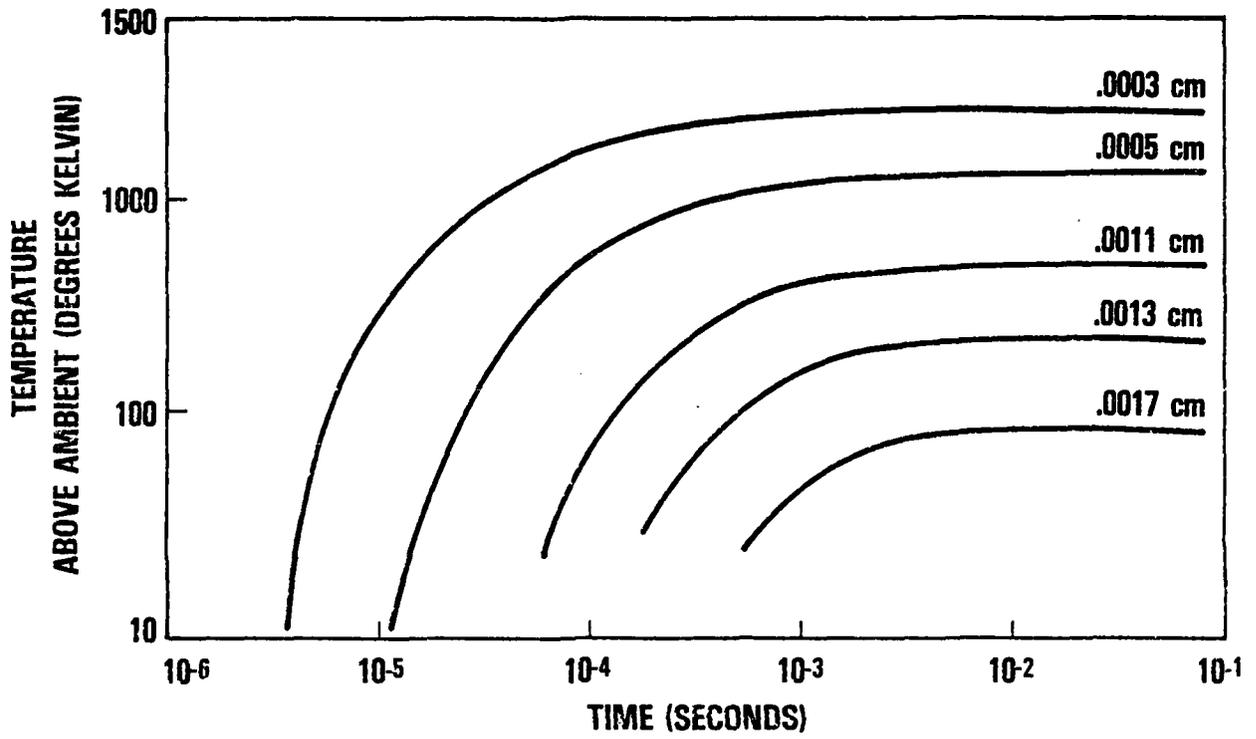
FIGURE 3a. CALCULATED TEMPERATURE RISE AS A FUNCTION OF TIME AT VARIOUS
DISTANCES AHEAD OF THE FLAME FRONT FOR EJC PROPELLANT
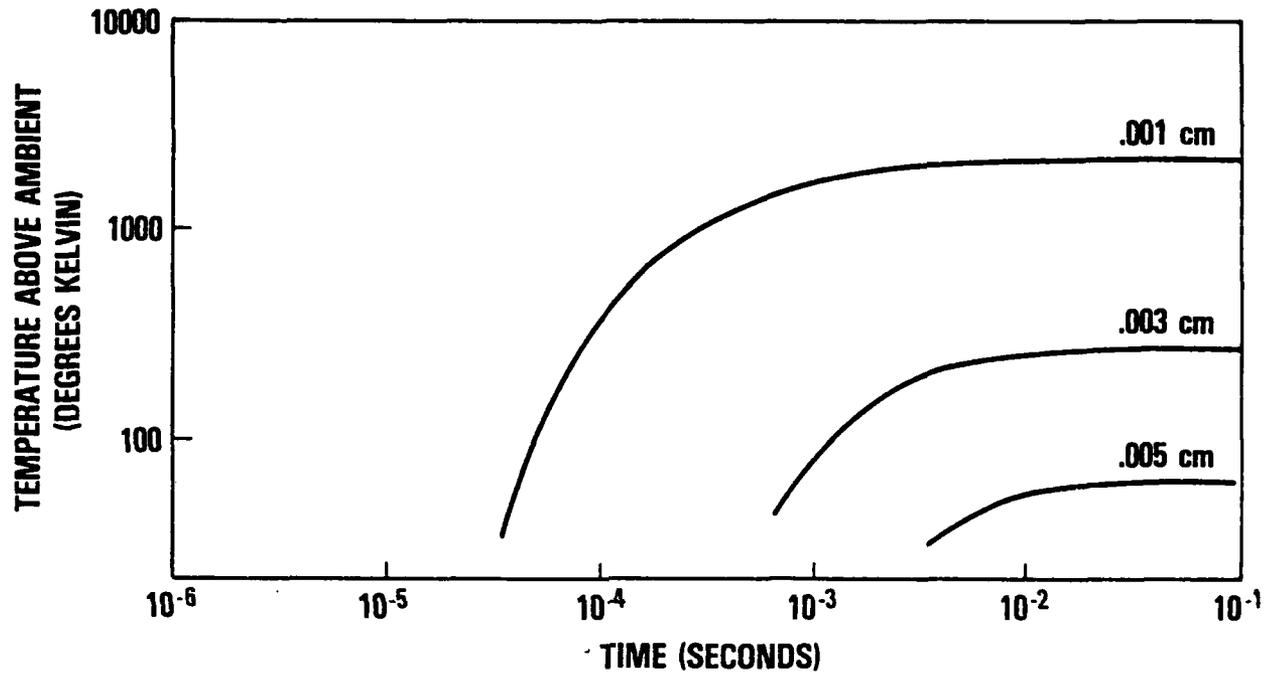
FIGURE 3b. CALCULATED TEMPERATURE RISE AS A FUNCTION OF TIME AT VARIOUS
DISTANCES AHEAD OF THE FLAME FRONT FOR TP-H-1148 PROPELLANT
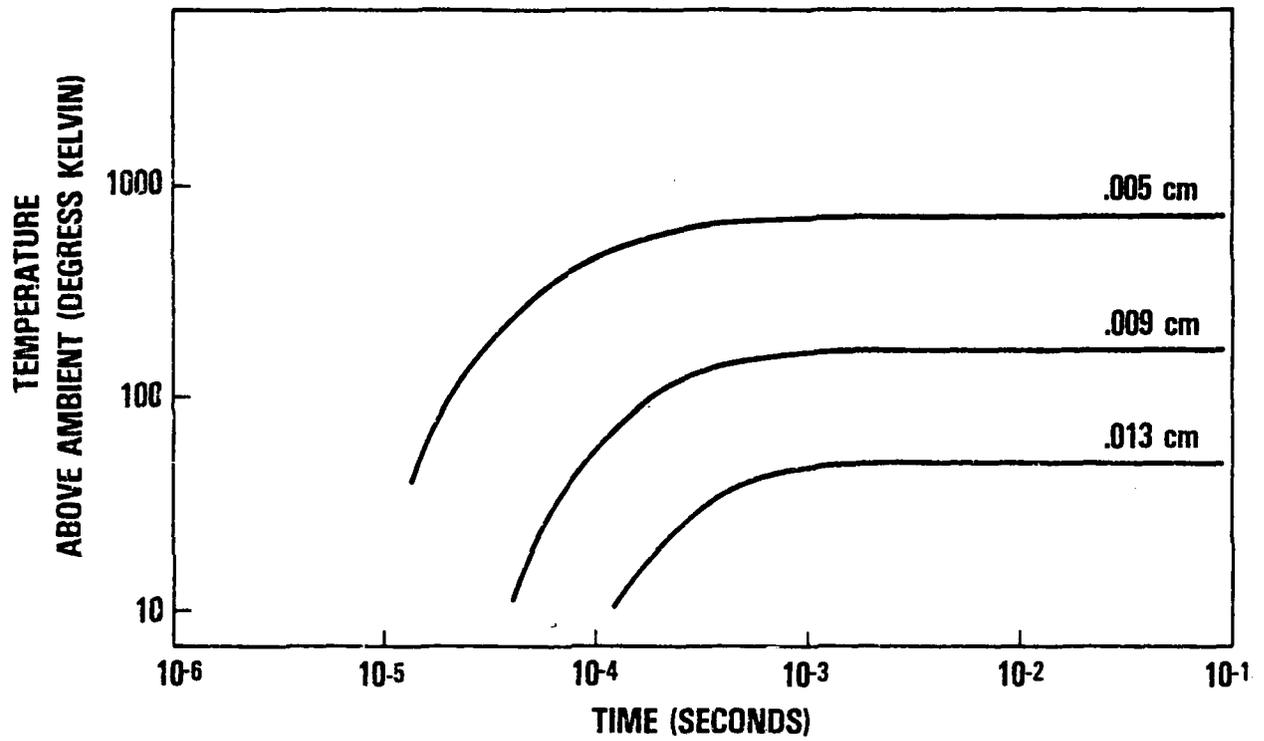
FIGURE 3c. CALCULATED TEMPERATURE RISE AS A FUNCTION OF TIME AT VARIOUS
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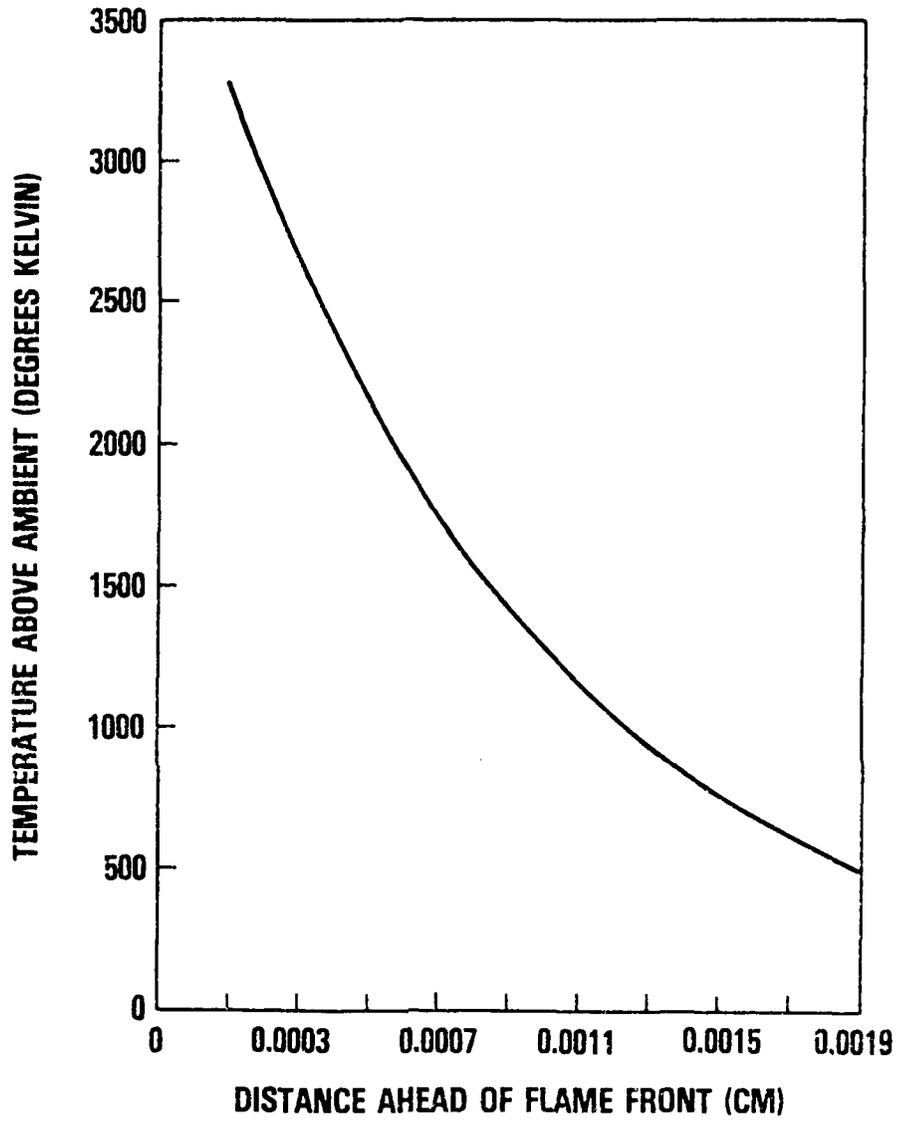
FIGURE 4a. CALCULATED "STEADY-STATE" TEMPERATURE RISE AS
A FUNCTION OF DISTANCE AHEAD OF THE FLAME FRONT
FOR EJC PROPELLANT (AT t = 0.045 sec)
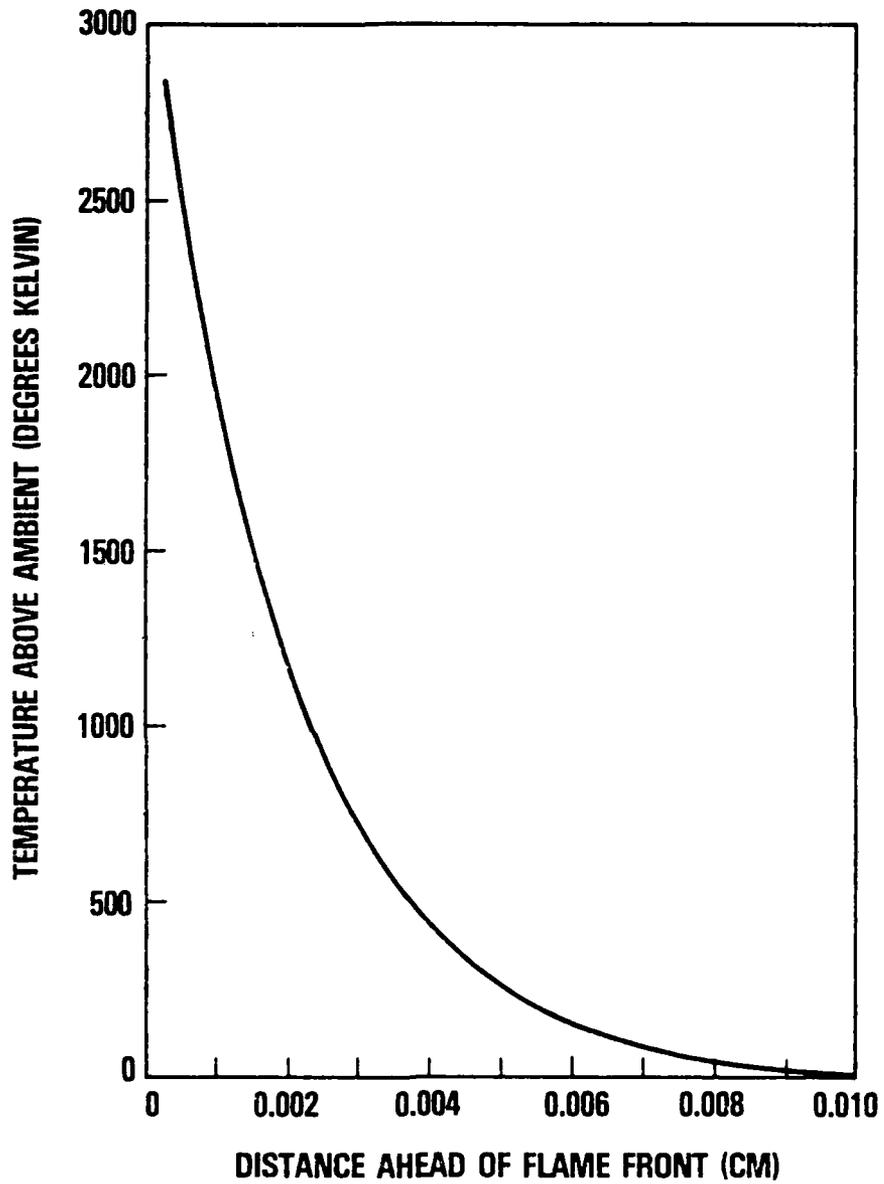
FIGURE 4b. CALCULATED "STEADY-STATE" TEMPERATURE RISE AS
A FUNCTION OF DISTANCE AHEAD OF THE FLAME FRONT
FOR TP-H-1148 PROPELLANT (AT t = 0.100 sec)
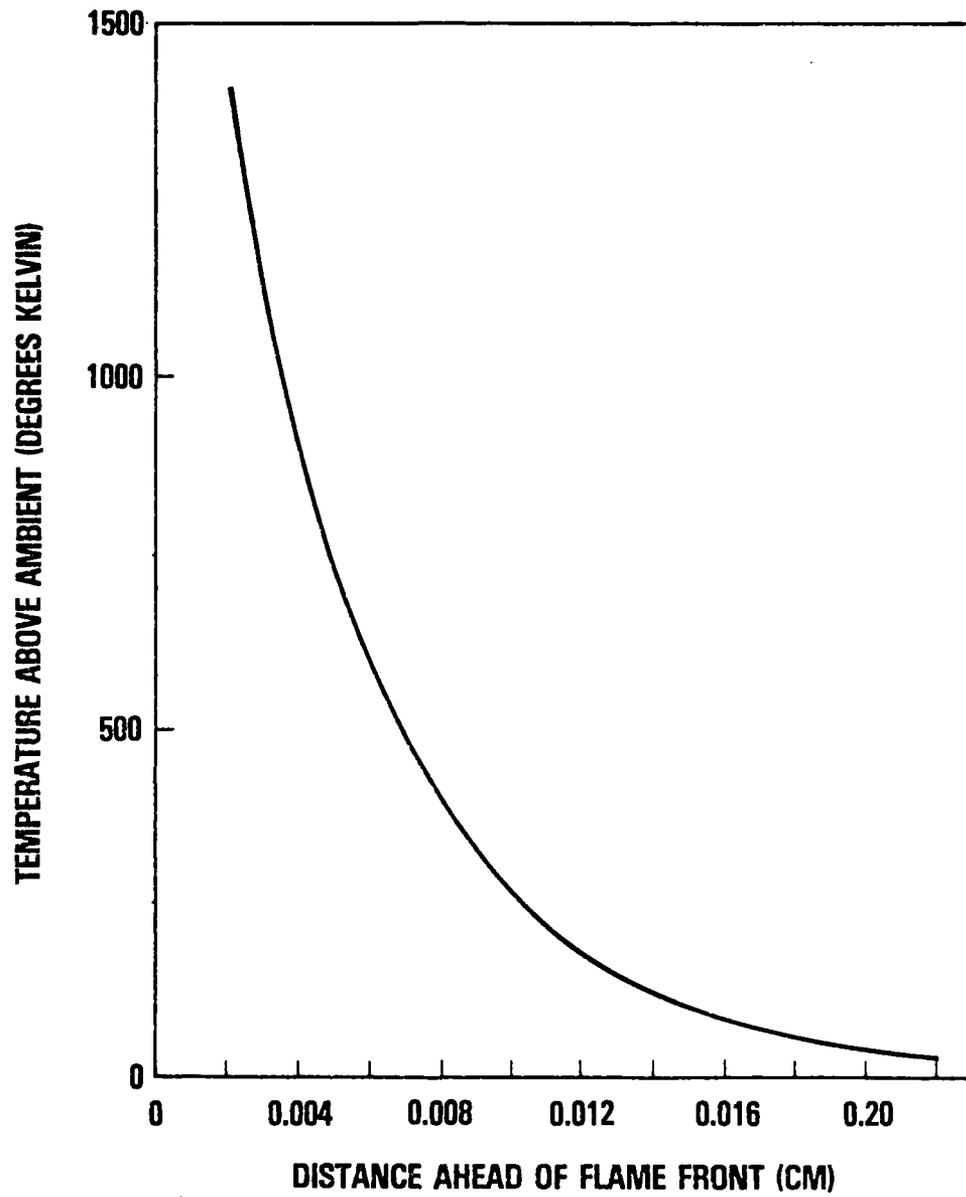
FIGURE 4c. CALCULATED "STEADY- STATE" TEMPERATURE RISE AS
A FUNCTION OF DISTANCE AHEAD OF THE FLAME FRONT
FOR PYRONOL PYROTECHNIC (AT t = 0.006 sec)

TABLE 1. DENSITY OF SOLID MATERIALS (ρ) AS WELL AS POWDERED
MATERIALS (ρ_0) FOR DIFFERENT TYPES OF CARBORUNDUM.
THE AVERAGE LINEAR DIMENSION (l) OF THE POWDERED MATERIAL
IS ALSO SHOWN. (REF. 6)

	CARBORUNDUM			
	NO. 40	NO. 90	NO. 280	NO. 600
ρ, g cm^{-3}	1·80	1·89	1·84	1·54
ρ_0, g cm^{-3}	3·20	3·20	3·20	3·20
l, cm	0·055	0·0194	0·0061	0·0027

TABLE 2. SELECTED PROPERTIES OF REACTIVE MATERIALS USED
FOR CALCULATION

MATERIAL	BURN VELOCITY (cm/sec)	FLAME TEMPERATURE	THERMAL DIFFUSIVITY (cm²/sec)
EJC PROPELLANT	1.372	3913.5	375.3
TP-H-1148 PROPELLANT	1.067	3429.6	229.6
PYRONOL PYROTECHNIC	41.58	2473.0	2.58

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